SECURITY INFORMATION

[redacted]

Copy 303
RM E52F25

[redacted]

NACA RM E52F25

6751

NACA

RESEARCH MEMORANDUM

SPREADING OF EXHAUST JET FROM 16-INCH RAM JET

AT MACH NUMBER 2.0

By Fred Wilcox and Donald Pennington

Lewis Flight Propulsion Laboratory
Cleveland, Ohio

Classification cancelled (or changed to UNCLASSIFIED)

By Authority of NASA Tech Pub Announcement #?
(OFFICER AUTHORIZED TO CHANGE)

By .... 28 Jul 58 ....
NAME AND

....
GRADE OF OFFICER MAKING CHANGE)

24 Mar 61
DATE

[redacted]

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
August 14, 1952

319.98/13

[redacted]

E

NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

RESEARCH MEMORANDUM

SPREADING OF EXHAUST JET FROM 16-INCH RAM JET AT MACH NUMBER 2.0

By Fred Wilcox and Donald Pennington

2594

SUMMARY

An investigation of the jet-spreading characteristics of a 16-inch ram-jet engine was conducted in the 8- by 6-foot supersonic tunnel at a Mach number of 2.0; both a converging nozzle having a contraction ratio of 0.71 and a cylindrical extension to the combustion chamber were used. The jet boundaries determined by means of pitot pressure surveys were compared with boundaries calculated from one-dimensional continuity and momentum relations.

For the cylindrical nozzle, the jet reaches its maximum diameter, 4 percent greater than calculated, about 0.6 nozzle-exit diameter downstream of the nozzle exit. The maximum diameter for the converging nozzle was 7 percent greater than calculated from one-dimensional relations and occurred from 1 to 1.5 nozzle-exit diameters downstream of the exit.

Nondimensional maximum jet diameters agreed closely with results of an investigation by Rousso and Baughman; these data were obtained with low-temperature jets exhausting into a stream at a Mach number of 1.91 from nozzles having exit diameters of 0.75 inch.

INTRODUCTION

Information on spreading characteristics of jets issuing from choked nozzles into supersonic streams has thus far been obtained from small models. In reference 1, jets were investigated for several 0.75-inch-diameter nozzles exhausting into a Mach number 1.91 stream. Air heated to 300° F was used in the jet, which had a ratio of total pressure at the exit to free-stream static pressure varying from 2.5 to 16. The jet boundary was obtained by means of a thermocouple rake.

Because the existing information was obtained with jets of small size and low temperature, it was desired to compare it with the trends reported with jets of larger diameter and higher gas temperature. A 16-inch-diameter jet with temperatures from 135° to 2640° F and pressure ratios from 2.65 to 5.35 was obtained with the 16-inch ram-jet engine reported in reference 2. The engine was operated in the Lewis 8- by 6-foot supersonic tunnel at a Mach number of 2.0 with a converging and a cylindrical exhaust nozzle. Jet boundaries were obtained to 2.7 nozzle-exit diameters downstream by means of a pitot pressure survey.

SYMBOLS

The following symbols are used in this report:

A^*/A_j ratio of area at nozzle exit to area for complete jet expansion

M Mach number

P total pressure

p static pressure

γ ratio of specific heats

Subscripts:

e exhaust nozzle exit

j condition in jet where value of static pressure is equal to ambient pressure

p pitot pressure

0 ambient

1 behind a normal shock occurring at free-stream Mach number

APPARATUS AND PROCEDURE

Installation of the ram-jet engine in the tunnel is shown schematically in figure 1. The engine and its mounting in the tunnel were the same as that described in reference 2. The engine diameter was 16 inches and its over-all length was 15.6 feet.

The two exhaust nozzles were the same as those reported in reference 2. The converging nozzle was 18 inches long and had a contraction ratio of 0.71. Its boattail half-angle was 4°. The cylindrical nozzle was an extension of the combustion chamber.

The can-type combustor reported in reference 2 (and utilized herein) employed propylene oxide for the cylindrical nozzle; preheated gasoline, introduced through a slightly modified fuel-injector system was used for the converging nozzle. For all the data presented, the engine diffuser was operated supercritically, that is, with no spillage of air. The tunnel Mach number was 2.0, and the pressure altitude was about 37,000 feet.

Jet boundaries were obtained from a survey of the jet made with the water-cooled movable rake shown in figures 1 and 2. It was mounted from the tunnel side wall 4 feet from the floor and extended across the exit jet. By means of a remote-controlled mechanism the rake could be
2594 positioned at any point from the nozzle exit to 2.7 nozzle diameters downstream. Locations of the static- and total-pressure tubes in the rake are given in table I. Only the tubes located in the region of the exhaust jet were water cooled, and these tubes were also used in computing the jet temperature by the methods employed in reference 2. The static tubes in the jet were made of 5/16-inch-outside-diameter Inconel tubing with orifices located 12 diameters downstream of the pointed tip.

RESULTS AND DISCUSSION

Typical rake data are shown in figure 3 for the converging nozzle operating at a nozzle pressure ratio P_e/p_0 of 5.35 and a total temperature of 1740° F. The data are presented as the ratio of pitot pressure to free-stream pitot pressure P_p/P_1. It should be mentioned that the pitot pressure is not the true total pressure, because of the loss across the normal shock in front of the pitot tube. Tabulated on the figure is the ratio of average static pressure in the jet to free-stream static pressure p/p_0. The static pressure in the jet was taken as the arithmetic average of readings from the three water-cooled static tubes, which gave a reasonably flat profile for all survey positions.

By definition the jet boundary is taken as the point of lowest measured total pressure. This point is in the mixing region between the low-energy air in the external boundary layer and the edge of the jet.

From figure 3(a) it is seen that when the rake position was 0.01 nozzle-exit diameter from the nozzle exit, the jet boundary occurred at the edge of the nozzle. The fact that the value of P_p/P_1 exceeded 1.0 at about 1.3 nozzle diameters from the center of the jet is physically justified because of the shock from the nozzle exit (which would also occur in flight) and the complicating influence of reflected oblique shocks from the tunnel wall. As the rake was moved from the nozzle exit to 0.45 nozzle-exit diameter downstream, the jet boundary spread to a radius of 0.59 nozzle-exit diameter, and the static pressure ratio p/p_0 decreased from 3.24 to 1.22.

The jet boundary for rake positions from 0.9 to 2.69 nozzle-exit diameters had a radius of about 0.65 nozzle-exit diameter (fig. 3(b)), and the values of p/p_0 in the jet were near 1.0, a condition indicating that beyond 0.9 diameter of the nozzle exit the jet is fully expanded. As the rake was moved from 0.9 to 2.69 nozzle-exit diameters, the total-pressure profile in the jet tended to slope less sharply at the edges of the jet. From the results of reference 3, it might be expected that temperature profiles for the jet would be similar to the total-pressure profiles.

A summary of jet-boundary data for the converging nozzle obtained from the rake is presented in figure 4. The data shown are for gas total temperatures ranging from 135° to 1740° F. Since the engine was operated supercritically, as the exit total temperature was increased (from 135° to 1740° F), the nozzle pressure ratio also increased (from 2.65 to 5.35). Combustion efficiencies were approximately 60 percent; the amount of combustion taking place in the jet is unknown.

In figure 4 the measured jet radius is compared with the calculated jet radius for one-dimensional expansion. In the calculation of jet radius, the theoretical jet Mach number M_j and the jet area ratio A^*/A_j were obtained from one-dimensional continuity and momentum relations for the exhaust jet between the nozzle-exit and free-stream conditions. The ratio of specific heats γ used was 1.4 for total temperatures below 300° F and 1.3 for higher temperatures, although the effect of variation in γ was slight. The method of characteristics also provides a means of predicting the jet boundary. For the present axially symmetric case, its use was not considered justified.

For the converging-nozzle data shown, no measurable jet expansion was observed for the lowest nozzle pressure ratio, 2.65. However, the jet spread an increasing amount as the pressure ratio was raised from 4.01 to 5.35. The maximum jet diameter was attained about 1 to 1.5 nozzle-exit diameters downstream of the nozzle exit. The measured jet radius was from 3 to 7 percent higher than the one-dimensional calculation with nozzle pressure ratios greater than 4.01. Factors which account for this increase are overexpansion of the jet, continued burning downstream of the nozzle exit, and mixing of air from the boundary layer on the outside of the tail pipe.

A curve from figure 15 of reference 1, for a nozzle pressure ratio of 4.6 with a converging nozzle in a Mach number 1.91 stream, is shown for comparison (fig. 4). For this case also, the maximum jet diameter was reached at about 1.5 nozzle-exit diameters downstream; the measured jet radius was 6 percent greater than the calculated. The boattail angle for the converging nozzle of reference 1 was 5.63° compared to 4° for this investigation, and the ratio of boundary-layer thickness to nozzle-exit diameter for reference 1 was roughly comparable with that for the cylindrical nozzle of this investigation. Close agreement between the data of reference 1 and the data obtained with the 16-inch ram jet was obtained to a distance of about 1.4 nozzle-exit diameters downstream.

A qualitative consideration (two-dimensional characteristics) of the effect of convergence angle on the orientation of the external shock and of expansion Mach lines from the exit indicated that shorter jet-expansion distances would be expected with the convergent as compared with the cylindrical nozzle. The actual data obtained with the cylindrical-nozzle configuration are shown in figure 5. In this case, the exit total temperatures varied from 1330° to 2640° F, and the nozzle pressure ratio varied from 3.04 to 4.5. Contrary to expectations, the jet expanded in a shorter axial distance than for the converging nozzle; the expansion reached a maximum (4 percent greater than calculated for a nozzle pressure ratio of 3.5) about 0.6 nozzle-exit diameter downstream.

2594

The maximum jet diameter might also be expected to be decreased by an increase in convergence angle. On the contrary, the ratio of maximum jet radius to nozzle-exit diameter was larger for the convergent nozzle than for the cylindrical nozzle at comparable pressure ratios. This observation results in part from the thinner boundary layer observed for the cylindrical nozzle as shown in figure 6. These boundary-layer profiles are typical of all operating conditions and were only slightly affected by exhaust-gas temperature in the range investigated. The boundary-layer curves were faired through data points obtained for opposite sides of the nozzle from the survey rake located at the nozzle exit. The thicker boundary layer of the convergent nozzle not only provides more low-energy air for mixing with the jet but also provides a cushion to weaken the strength of the oblique shock at the exit and hence to increase the expansion angle at the jet exit.

SUMMARY OR RESULTS

From an investigation of jet spreading downstream of a 16-inch ram-jet engine operating at exhaust-gas total temperatures from 135° to 2640° F, with both a converging and a cylindrical exit nozzle in a Mach number 2.0 supersonic stream, the following results were obtained:

1. The maximum diameter of the jet exceeded the one-dimensional calculation by about 7 percent of the radius for the converging nozzle and 4 percent for the cylindrical nozzle.

2. The jet reached its maximum diameter from 1 to 1.5 nozzle-exit diameters downstream for the converging nozzle and about 0.6 diameter downstream for the cylindrical extension to the combustion chamber.

3. Nondimensional maximum jet diameters agreed closely with previous results which were obtained on small-scale models operating at much lower temperatures. 2594

Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio

REFERENCES

1. Rousso, Morris D., and Baughman, L. Eugene: Investigation at Mach Number 1.91 of Spreading Characteristics of Jet Expanding from Choked Nozzles. NACA RM E51L19, 1952.

2. Perchonok, Eugene, Wilcox, Fred, and Pennington, Donald: Effect of Angle of Attack and Exit Nozzle Design on the Performance of a 16-Inch Ram Jet at Mach Numbers from 1.5 to 2.0. NACA RM E51G26, 1951.

3. Rousso, Morris D., and Kochendorfer, Fred D.: Velocity and Temperature Fields in Circular Jet Expanding from Choked Nozzle into Quiescent Air. NACA RM E51F18, 1951. (Supersedes NACA RM E50E03a.)

2594

TABLE I - PRESSURE-TUBE LOCATIONS FOR JET SURVEY RAKE

Uncooled tubes		Water-cooled tubes	
Distance from jet centerline (in.) left side (looking downstream)	Tube	Distance from jet centerline (in.) +left side -right side	Tube
		10.61	Total
		9.87	Total
		9.12	Total
		8.56	Total
		8.12	Total
		7.61	Total
30.94	Total	7.25	Total
28.50	Static	6.87	Total
26.12	Total	6.44	Total
23.61	Static	6.00	Total
21.25	Total	5.50	Total
18.87	Total	4.94	Total
16.37	Total	2.61	Static
13.94	Static	.19	Static
		-1.39	Total
		-3.13	Total
		-4.69	Static
		-6.19	Total
		-6.56	Total
		-7.00	Total
		-7.39	Total
		-7.81	Total
		-8.31	Total
		-8.81	Total
		-9.56	Total
		-10.31	Total
		-11.25	Total

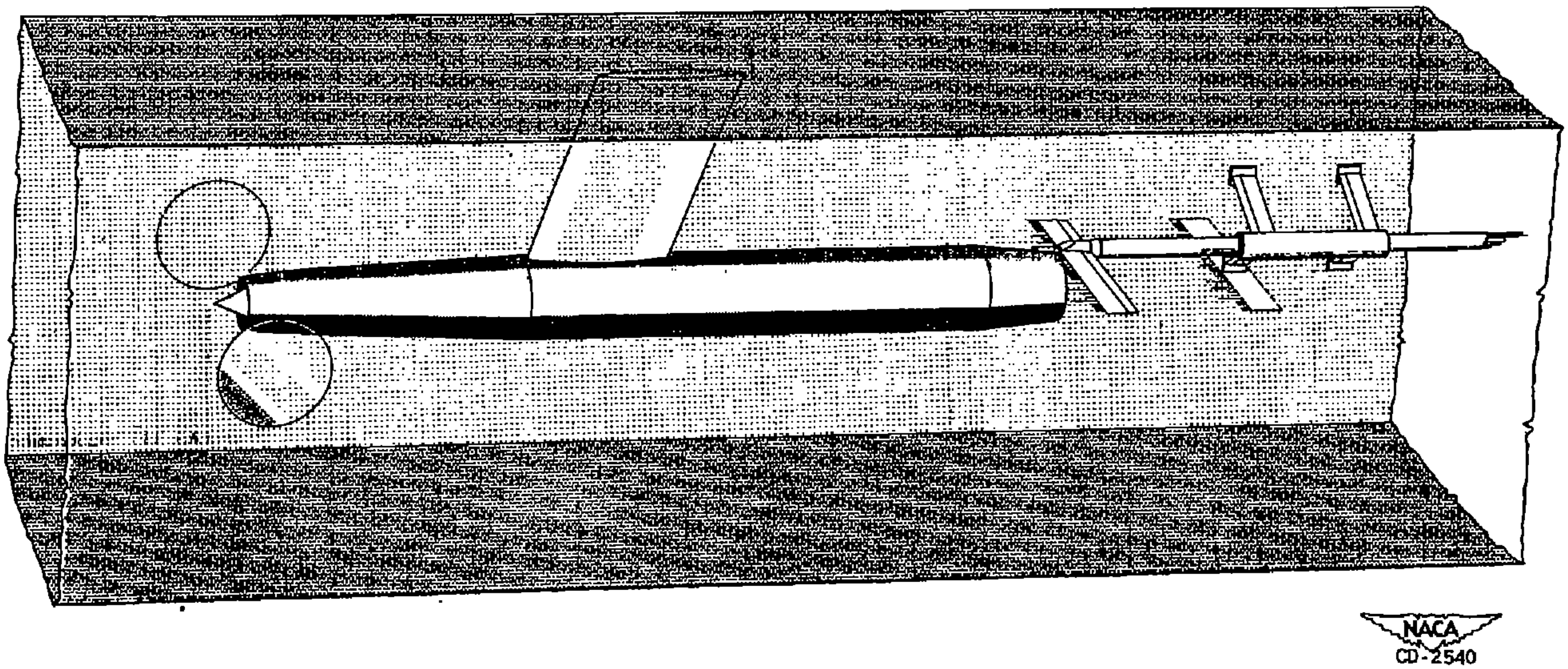
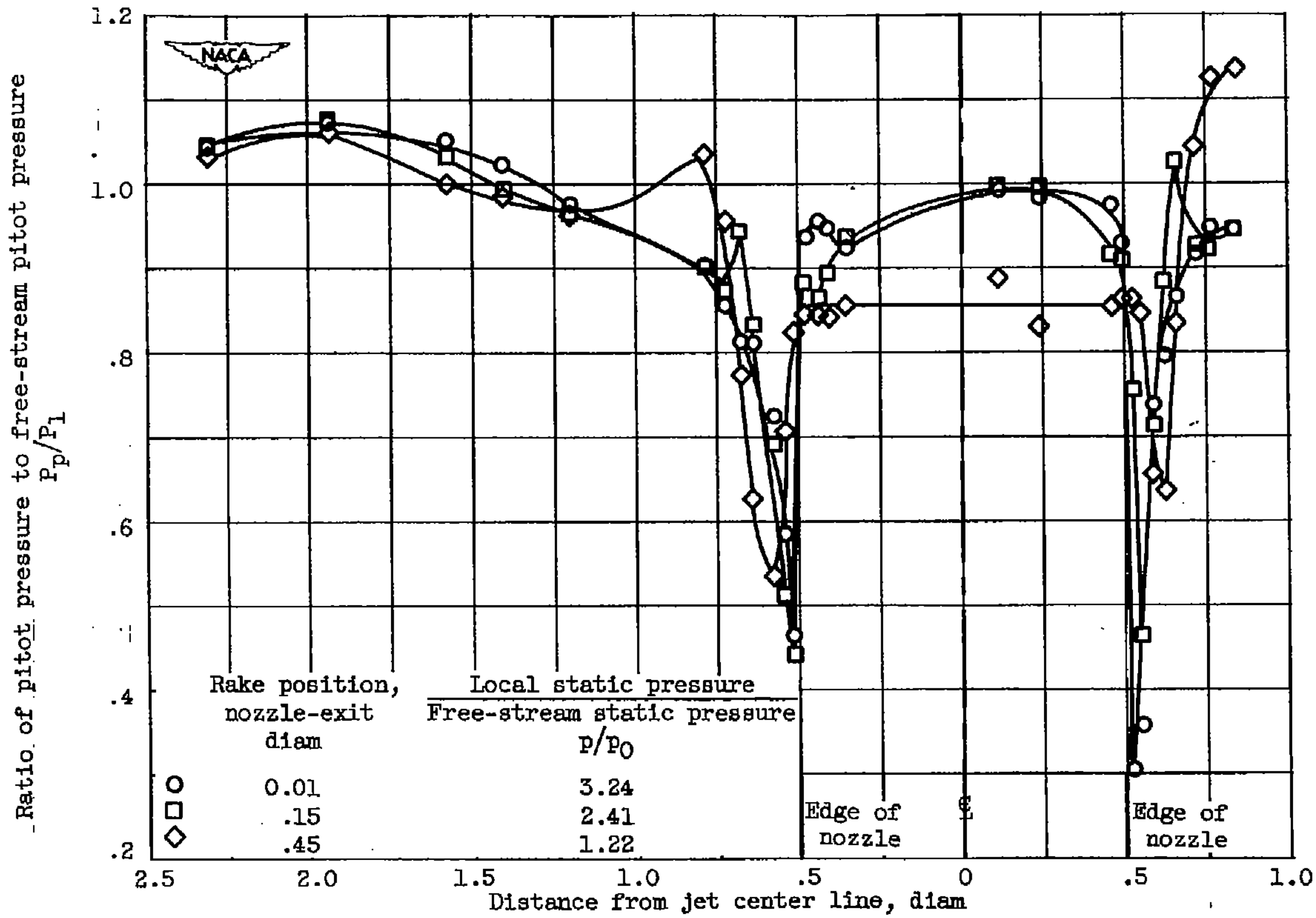


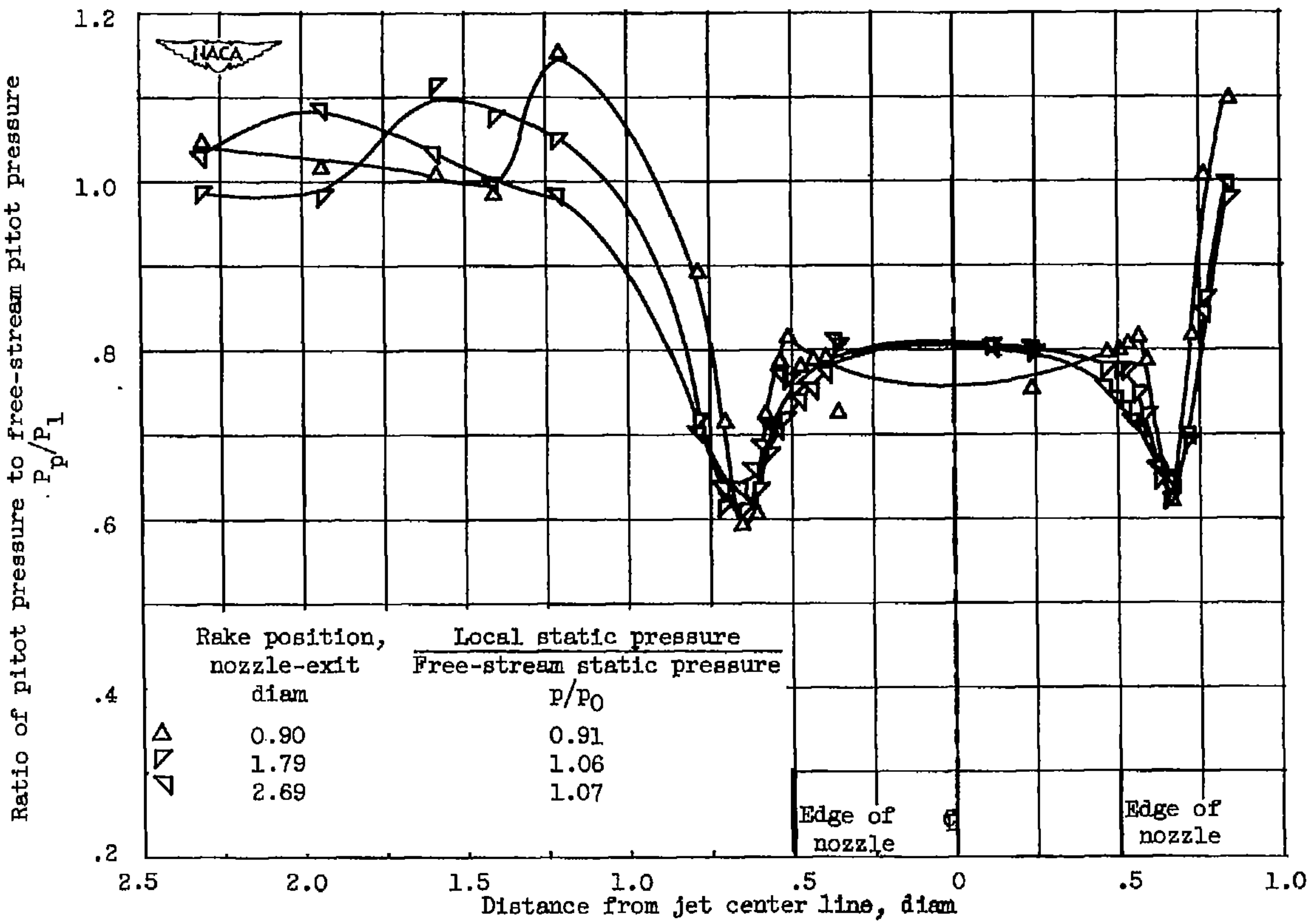
Figure 1. - Schematic diagram of installation of 16-inch ram-jet engine in 8- by 6-foot supersonic tunnel.

Figure 2. - View downstream in tunnel test section showing rear of engine and movable survey rake in retracted position.



(a) Survey at 0.01, 0.15, and 0.45 nozzle-exit diameter.

Figure 3. - Wake survey behind engine for converging nozzle. Jet total temperature, 1740° F; nozzle pressure ratio P_e/p_0, 5.35.



(b) Survey at 0.90, 1.79, and 2.69 nozzle-exit diameters.

Figure 3. - Concluded. Wake survey behind engine for converging nozzle. Jet total temperature, 1740° F; nozzle pressure ratio P_e/p_0, 5.35

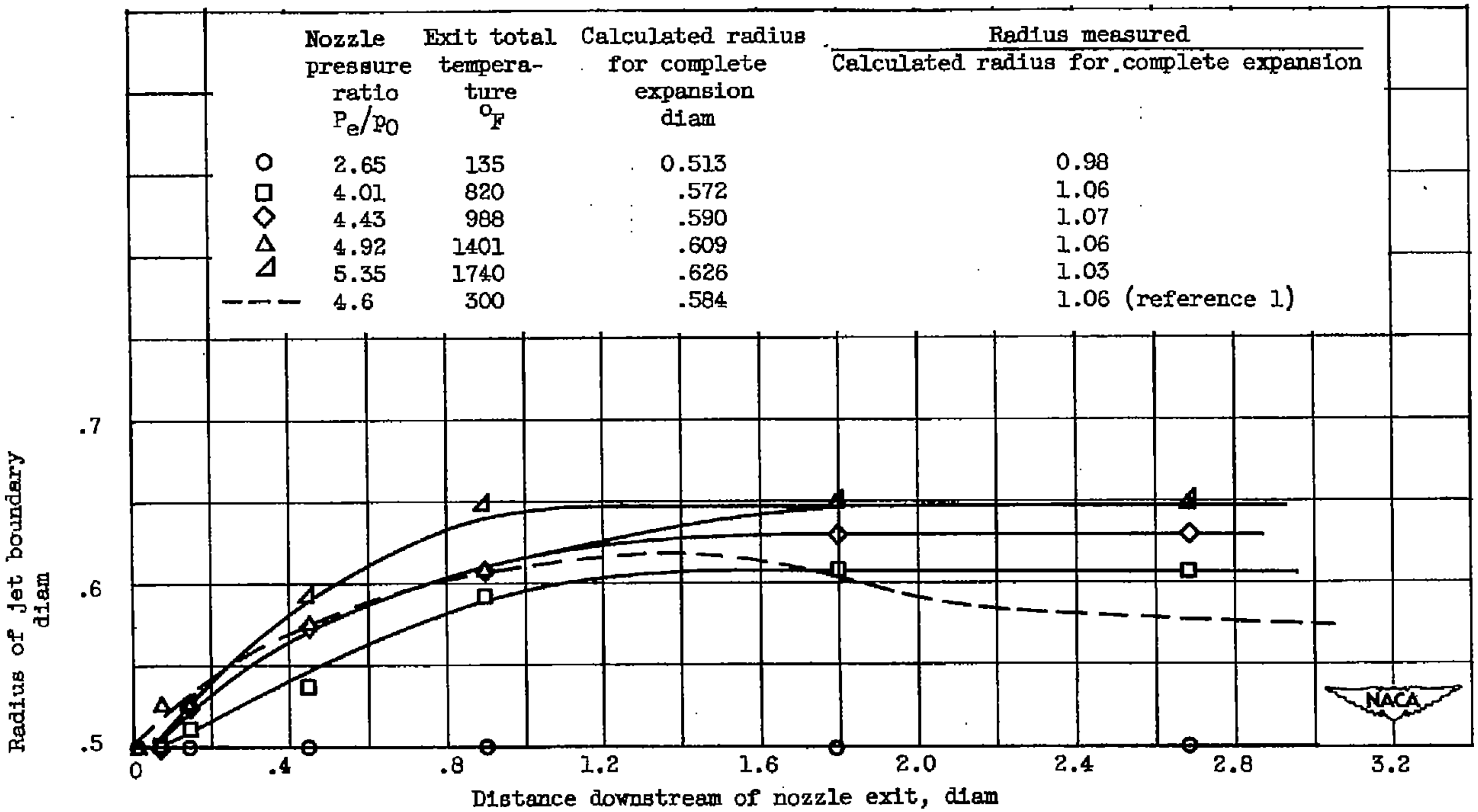


Figure 4. - Spreading of jet from converging nozzle.

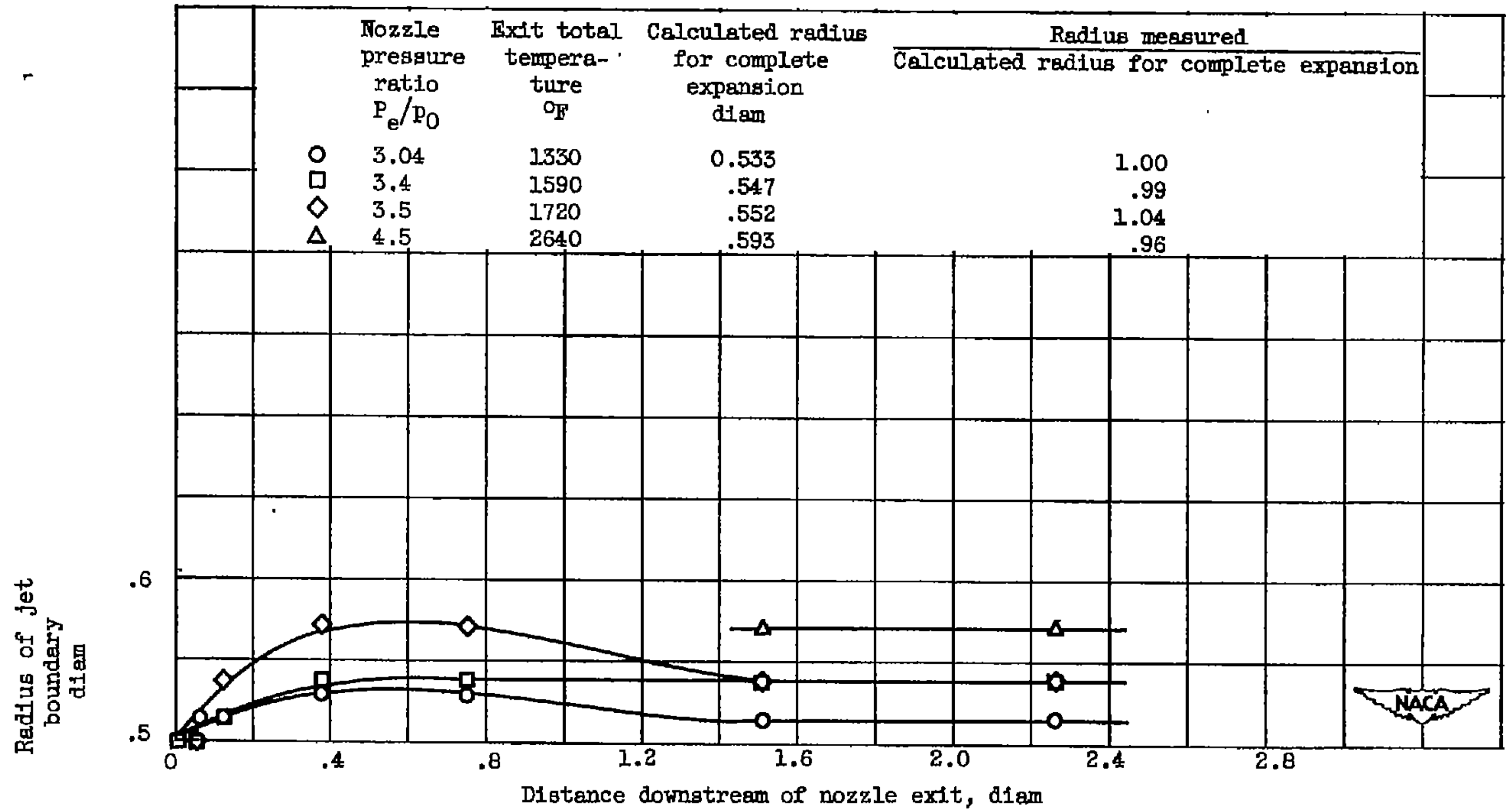


Figure 5. - Spreading of jet from cylindrical nozzle.

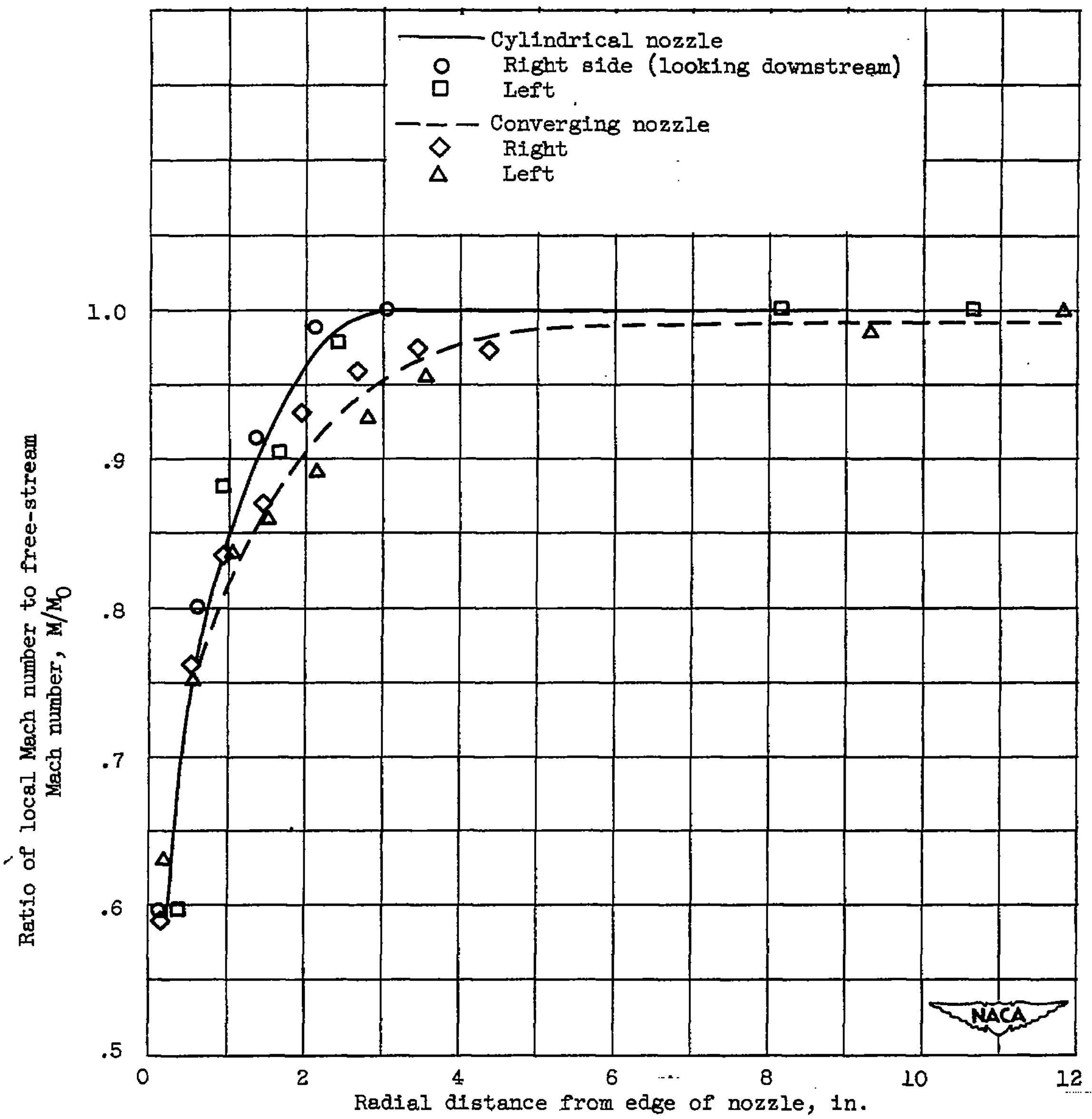


Figure 6. - Typical boundary-layer profiles for two exhaust nozzles.

NACA-Langley - 8-14-52 - 450